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14. ABSTRACT
Optical lattices are employed to simulate important condensed matter materials, with ultracold atoms playing the role of the electrons in a real material. We have obtained the phase diagram of a one-dimensional (1D) Fermi gas with spin-imbalance in this way. This system features a partially polarized phase which is the 1D analog of the long-sought FFLO state. Current research is focused on direct detection of the FFLO state and explore the 1D-3D dimensional crossover. We have recently detected antiferromagnetic order in the 3D Fermi-Hubbard model using

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ABSTRACT

Optical lattices are employed to simulate important condensed matter materials, with ultracold atoms playing the role of the electrons in a real material. We have obtained the phase diagram of a one-dimensional (1D) Fermi gas with spin-imbalance in this way. This system features a partially polarized phase which is the 1D analog of the long-sought FFLO state. Current research is focused on direct detection of the FFLO state and explore the 1D-3D dimensional crossover. We have recently detected antiferromagnetic order in the 3D Fermi-Hubbard model using spin-dependent Bragg scattering of light. This was a major goal of our project, enabled by the development of a novel scheme to evaporatively cool atoms in an optical lattice. We have also focused on developing alternative cooling schemes, We have also investigated the connection between quantum integrability and thermalization in a 1D Bose gas, and considered equilibration and thermalization phenomena in optical lattices. Other theoretical issues, such as the effects of spin-orbit coupling, the disordered Bose-Hubbard model, and many-body localization, have also been explored.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/16/2012	20.00	R. Hart, J. Hitchcock, P. Duarte, T. Corcovilos, T.-L. Yang, A. Reed, R. Hulet. All-optical production of a lithium quantum gas using narrow-line laser cooling, Physical Review A, (12 2011): 0. doi: 10.1103/PhysRevA.84.061406
08/16/2012	47.00	David Huse, Randall Hulet, Charles Mathy. Enlarging and cooling the Néel state in an optical lattice, Physical Review A, (8 2012): 0. doi: 10.1103/PhysRevA.86.023606
08/16/2012	46.00	E. N. Duchon, Y. Kato, N. Kawashima, R. T. Scalettar, N. Trivedi, K. W. Mahmud. Finite-temperature study of bosons in a two-dimensional optical lattice, Physical Review B, (08 2011): 0. doi: 10.1103/PhysRevB.84.054302
08/16/2012	45.00	S. Pathak, N. Trivedi, S. Chang. Repulsive fermions in optical lattices: Phase separation versus coexistence of antiferromagnetism and d-wave superfluidity, Physical Review A, (01 2012): 0. doi: 10.1103/PhysRevA.85.013625
08/16/2012	44.00	Yen Lee Loh, Nandini Trivedi, Mason Swanson. Proposal for interferometric detection of the topological character of modulated superfluidity in ultracold Fermi gases, New Journal of Physics, (03 2012): 0. doi: 10.1088/1367-2630/14/3/033036
08/16/2012	43.00	Han Pu, Keye Zhang, Xing-Dong Zhao, Weiping Zhang, Lu Zhou. Cavity-induced switching between localized and extended states in a noninteracting Bose-Einstein condensate, Physical Review A, (10 2011): 0. doi: 10.1103/PhysRevA.84.043606
08/16/2012	42.00	Xia-Ji Liu, Hui Hu, Han Pu, Lei Jiang. Rashba spin-orbit-coupled atomic Fermi gases, Physical Review A, (12 2011): 0. doi: 10.1103/PhysRevA.84.063618
08/16/2012	41.00	Hui Hu, B. Ramachandhran, Han Pu, Xia-Ji Liu. Spin-Orbit Coupled Weakly Interacting Bose-Einstein Condensates in Harmonic Traps, Physical Review Letters, (01 2012): 0. doi: 10.1103/PhysRevLett.108.010402
08/16/2012	40.00	Bogdan Opanchuk, Xia-Ji Liu, Han Pu, Peter D. Drummond, B. Ramachandhran, Hui Hu. Half-quantum vortex state in a spin-orbit-coupled Bose-Einstein condensate, Physical Review A, (02 2012): 0. doi: 10.1103/PhysRevA.85.023606
08/16/2012	36.00	Fei Lin, Erik Sørensen, D. Ceperley. Superfluid-insulator transition in the disordered two-dimensional Bose-Hubbard model, Physical Review B, (09 2011): 0. doi: 10.1103/PhysRevB.84.094507
08/16/2012	35.00	Paul Ginsparg, Erich Mueller, Eliot Kapit. Non-Abelian Braiding of Lattice Bosons, Physical Review Letters, (02 2012): 0. doi: 10.1103/PhysRevLett.108.066802
08/16/2012	39.00	L. Baksmaty, C. Bolech, Han Pu, Hong Lu. Expansion of 1D Polarized Superfluids: The Fulde-Ferrell-Larkin-Ovchinnikov State Reveals Itself, Physical Review Letters, (05 2012): 0. doi: 10.1103/PhysRevLett.108.225302
08/16/2012	38.00	Michael Kolodrubetz, Bryan Clark, David Huse. Nonequilibrium Dynamic Critical Scaling of the Quantum Ising Chain, Physical Review Letters, (07 2012): 0. doi: 10.1103/PhysRevLett.109.015701
08/16/2012	37.00	David Huse, Hyungwon Kim. Superdiffusive nonequilibrium motion of an impurity in a Fermi sea, Physical Review A, (04 2012): 0. doi: 10.1103/PhysRevA.85.043603
08/16/2012	34.00	Stefan Natu, David McKay, Brian DeMarco, Erich Mueller. Evolution of condensate fraction during rapid lattice ramps, Physical Review A, (06 2012): 0. doi: 10.1103/PhysRevA.85.061601

08/16/2012	33.00	W. Vincent Liu, Andreas Hemmerich, S. Das Sarma, Kai Sun. Topological semimetal in a fermionic optical lattice, Nature Physics, (11 2011): 0. doi: 10.1038/nphys2134
08/16/2012	32.00	Philipp Hauke, Erhai Zhao, Krittika Goyal, Ivan Deutsch, W. Vincent Liu, Maciej Lewenstein. Orbital order of spinless fermions near an optical Feshbach resonance, Physical Review A, (11 2011): 0. doi: 10.1103/PhysRevA.84.051603
08/16/2012	31.00	Zixu Zhang, Xiaopeng Li, W. Vincent Liu. Stripe, checkerboard, and liquid-crystal ordering from anisotropic p-orbital Fermi surfaces in optical lattices, Physical Review A, (05 2012): 0. doi: 10.1103/PhysRevA.85.053606
08/16/2012	30.00	Zixu Zhang, Xiaopeng Li, W. Liu. Time-Reversal Symmetry Breaking of p-Orbital Bosons in a One-Dimensional Optical Lattice, Physical Review Letters, (04 2012): 0. doi: 10.1103/PhysRevLett.108.175302
08/16/2012	28.00	Xi-wen Guan, Tin-Lun Ho. Quantum criticality of a one-dimensional attractive Fermi gas, Physical Review A, (08 2011): 0. doi: 10.1103/PhysRevA.84.023616
08/16/2012	27.00	Shizhong Zhang, Tin-Lun Ho. Atom loss maximum in ultra-cold Fermi gases, New Journal of Physics, (05 2011): 0. doi: 10.1088/1367-2630/13/5/055003
08/16/2012	29.00	Tin-Lun Ho, Shizhong Zhang. Bose-Einstein Condensates with Spin-Orbit Interaction, Physical Review Letters, (10 2011): 0. doi: 10.1103/PhysRevLett.107.150403
08/16/2012	26.00	Vijay Shenoy, Tin-Lun Ho. Nature and Properties of a Repulsive Fermi Gas in the Upper Branch of the Energy Spectrum, Physical Review Letters, (11 2011): 0. doi: 10.1103/PhysRevLett.107.210401
08/16/2012	25.00	Tin-Lun Ho, Hui Zhai, Biao Lian. Searching for non-Abelian phases in the Bose-Einstein condensate of dysprosium, Physical Review A, (05 2012): 0. doi: 10.1103/PhysRevA.85.051606
08/16/2012	24.00	Tin-Lun Ho, Xiaoling Cui, Weiran Li. Alternative Route to Strong Interaction: Narrow Feshbach Resonance, Physical Review Letters, (06 2012): 0. doi: 10.1103/PhysRevLett.108.250401
08/16/2012	23.00	Weiran Li, Tin-Lun Ho. Bose Gases near Unitarity, Physical Review Letters, (05 2012): 0. doi: 10.1103/PhysRevLett.108.195301
08/16/2012	22.00	S. S. Kondov, W. R. McGehee, J. J. Zirbel, B. DeMarco. Three-Dimensional Anderson Localization of Ultracold Matter, Science, (10 2011): 0. doi: 10.1126/science.1209019
08/16/2012	19.00	C. Bolech, Kuei Sun. Oscillatory pairing amplitude and magnetic compressible-incompressible transitions in imbalanced fermionic superfluids in optical lattices of elongated tubes, Physical Review A, (05 2012): 0. doi: 10.1103/PhysRevA.85.051607
08/16/2012	21.00	Y. Liao, M. Revelle, T. Paprotta, A. Rittner, Wenhui Li, G. Partridge, R. Hulet. Metastability in Spin-Polarized Fermi Gases, Physical Review Letters, (09 2011): 0. doi: 10.1103/PhysRevLett.107.145305
08/29/2011	8.00	D. Ceperley, Shiwei Zhang, S. Zhou. Validity of the scattering-length approximation in strongly interacting Fermi systems, Physical Review A, (7 2011): 0. doi: 10.1103/PhysRevA.84.013625
08/29/2011	1.00	Paata Kakashvili, C. Bolech, H. Pu, S. Bhongale. Dissipative transport of trapped Bose-Einstein condensates through disorder, Physical Review A, (11 2010): 0. doi: 10.1103/PhysRevA.82.053632
08/29/2011	2.00	Han Pu, Yan Chen, Lei Jiang, Leslie Baksmaty, Hui Hu. Single impurity in ultracold Fermi superfluids, Physical Review A, (6 2011): 0. doi: 10.1103/PhysRevA.83.061604

08/29/2011 3.00 L O Baksmaty, Hong Lu, C J Bolech, Han Pu. A Bogoliubov–de Gennes study of trapped spin-imbalanced unitary Fermi gases,
New Journal of Physics, (05 2011): 0. doi: 10.1088/1367-2630/13/5/055014

08/29/2011 4.00 Ying Dong, Jinwu Ye, Han Pu. Multistability in an optomechanical system with a two-component Bose-Einstein condensate,
Physical Review A, (3 2011): 0. doi: 10.1103/PhysRevA.83.031608

08/29/2011 5.00 Stefan Natu, Kaden Hazzard, Erich Mueller. Local Versus Global Equilibration near the Bosonic Mott-Insulator–Superfluid Transition,
Physical Review Letters, (3 2011): 125301. doi: 10.1103/PhysRevLett.106.125301

08/29/2011 6.00 David Chen, Matthew White, Cecilia Borries, Brian DeMarco. Quantum Quench of an Atomic Mott Insulator,
Physical Review Letters, (6 2011): 235304. doi: 10.1103/PhysRevLett.106.235304

08/29/2011 7.00 D C McKay, B DeMarco. Cooling in strongly correlated optical lattices: prospects and challenges,
Reports on Progress in Physics, (05 2011): 54401. doi: 10.1088/0034-4885/74/5/054401

08/29/2011 9.00 Chia-Chen Chang, Shiwei Zhang, David Ceperley. Itinerant ferromagnetism in a Fermi gas with contact interaction: Magnetic properties in a dilute Hubbard model,
Physical Review A, (12 2010): 0. doi: 10.1103/PhysRevA.82.061603

08/29/2011 10.00 Arijeet Pal, David Huse. Many-body localization phase transition,
Physical Review B, (11 2010): 0. doi: 10.1103/PhysRevB.82.174411

08/29/2011 11.00 Charles Mathy, Meera Parish, David Huse. Trimers, Molecules, and Polarons in Mass-Imbalanced Atomic Fermi Gases,
Physical Review Letters, (4 2011): 0. doi: 10.1103/PhysRevLett.106.166404

08/29/2011 12.00 Eliot Kapit, Erich Mueller. Optical-lattice Hamiltonians for relativistic quantum electrodynamics,
Physical Review A, (3 2011): 33625. doi: 10.1103/PhysRevA.83.033625

08/29/2011 13.00 Kaden Hazzard, Erich Mueller. Techniques to measure quantum criticality in cold atoms,
Physical Review A, (7 2011): 0. doi: 10.1103/PhysRevA.84.013604

08/29/2011 14.00 Stefan Natu, Erich Mueller. Domain-wall dynamics in a two-component Bose-Mott insulator,
Physical Review A, (7 2010): 0. doi: 10.1103/PhysRevA.82.013612

08/29/2011 15.00 Yean-an Liao, Ann Sophie C. Rittner, Tobias Paprotta, Wenhui Li, Guthrie B. Partridge, Randall G. Hulet, Stefan K. Baur, Erich J. Mueller. Spin-imbalance in a one-dimensional Fermi gas,
Nature, (9 2010): 567. doi: 10.1038/nature09393

08/30/2011 16.00 Xiaopeng Li, W. Liu, Chungwei Lin. U(1) × U(1) to Z_{2} Kosterlitz-Thouless transition of the Larkin-Ovchinnikov phase in an anisotropic two-dimensional system,
Physical Review B, (3 2011): 92501. doi: 10.1103/PhysRevB.83.092501

08/31/2011 17.00 Richard Scalettar, Nandini Trivedi, Thereza Paiva, Yen Loh, Mohit Randeria. Fermions in 3D Optical Lattices: Cooling Protocol to Obtain Antiferromagnetism,
Physical Review Letters, (8 2011): 86401. doi: 10.1103/PhysRevLett.107.086401

08/31/2011 18.00 S.-Y. Chang, M. Randeria, N. Trivedi. Ferromagnetism in the upper branch of the Feshbach resonance and the hard-sphere Fermi gas,
Proceedings of the National Academy of Sciences, (12 2010): 51. doi: 10.1073/pnas.1011990108

09/19/2013 49.00 Paata Kakashvili, S. Bhongale, Han Pu, C. Bolech. Signatures of strong correlations in one-dimensional ultracold atomic Fermi gases,
Physical Review A, (10 2008): 0. doi: 10.1103/PhysRevA.78.041602

09/19/2013 48.00 Lei Jiang, Hui Hu, Han Pu, Yan Chen, Xia-Ji Liu. Universal Impurity-Induced Bound State in Topological Superfluids,
Physical Review Letters, (01 2013): 0. doi: 10.1103/PhysRevLett.110.020401

TOTAL: 49

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
09/20/2013	50.00	D.M. Ceperley, E.J. Mueller, M. Casula. Quantum Monte Carlo study of one-dimensional trapped fermions with attractive contact interactions, , ( ): 0. doi:
09/20/2013	54.00	W. Vincent Liu, Erhai Zhou. Theory of quasi-one-dimensional imbalanced Fermi gases, , (12 2008): 0. doi:
09/20/2013	57.00	David A. Huse, Rahul Nandkishore, Vadim Oganesyan, Arijeet Pal, S.L. Sondhi. Localization-protected quantum order, , (07 2013): 0. doi:
09/20/2013	56.00	Adrian E. Feiguin, David A. Huse. Spectral properties of a partially spin-polarized one-dimensional Hubbard/Luttinger superfluid, , (03 2009): 0. doi:
09/20/2013	55.00	Paata Kakashvili, C.J. Bolech. Paired states in spin-imbalanced atomic Fermi gases in one dimension, , (04 2009): 0. doi:
09/20/2013	60.00	B. Ramachandhran, Hui Hu, Han Pu. Emergence of topological and strongly correlated ground states in trapped Rashba spin-orbit-coupled Bose gases, , (03 2013): 0. doi:
09/20/2013	59.00	Lin Dong, Lei Jiang, Hui Hu, Han Pu. Finite-momentum dimer bound state in a spin-orbit-coupled Fermi gas, , (04 2013): 0. doi:
09/20/2013	58.00	Ying Dong, Han Pu. Spin mixing in spinor Fermi gases, , (04 2013): 0. doi:
09/20/2013	61.00	Lu Zhou, Han Pu, Weiping Zhang. Anderson localization of cold atomic gases with effective spin-orbit interaction in a quasiperiodic optical lattice, , (02 2013): 0. doi:
09/20/2013	53.00	M. White, M. Pasienski, D. McKay, S.Q. Zhou, D. Ceperley, B. DeMarco. Strongly Interacting Bosons in a Disordered Optical Lattice, , (02 2009): 0. doi:
09/20/2013	52.00	C.J.M. Mathy, David A. Huse. Accessing the Néel phase of ultracold fermionic atoms in a simple-cubic optical lattice, , (06 2009): 0. doi:
09/20/2013	51.00	Tin-Lun Ho, Qi Zhou. Squeezing out the entropy of fermions in optical lattices, , (04 2009): 0. doi:
09/23/2013	72.00	Jean-Félix Riou, Laura A. Zundel, David S. Weiss, Shuming Li, Ana Maria Rey, Aaron Reinhard, Rafael Hipolito. Self-Trapping in an Array of Coupled 1D Bose Gases, , (01 2013): 0. doi:
09/23/2013	73.00	Shuming Li (???), Salvatore R. Manmana, Ana Maria Rey, Rafael Hipolito, Aaron Reinhard, Jean-Félix Riou, Laura A. Zundel, David S. Weiss. Self-trapping dynamics in a two-dimensional optical lattice, , (08 2013): 0. doi:
09/23/2013	74.00	Ushnish Ray, David M. Ceperley . Revealing the condensate and noncondensate distributions in the inhomogeneous Bose-Hubbard model, , (05 2013): 0. doi:

09/23/2013 75.00 Kuei Sun, C. J. Bolech . Pair tunneling, phase separation, and dimensional crossover in imbalanced fermionic superfluids in a coupled array of tubes,
, (05 2013): 0. doi:

09/23/2013 76.00 William S. Cole, Shizhong Zhang, Arun Paramekanti, Nandini Trived. Bose-Hubbard Models with Synthetic Spin-Orbit Coupling: Mott Insulators, Spin Textures, and Superfluidity,
, (08 2013): 0. doi:

09/23/2013 77.00 Lin Dong, Lei Jiang, Han Pu. Fulde–Ferrell pairing instability in spin–orbit coupled Fermi gas,
, (07 2013): 0. doi:

09/23/2013 78.00 C J Bolech, F. Heidrich-Meisner, S. Langer, I. P. McCulloch, G. Orso, M. Rigol. Expansion after a geometric quench of an atomic polarized attractive Fermi gas in one dimension,
, (02 2013): 0. doi:

09/23/2013 79.00 Meera M. Parish, Stefan K. Baur, Erich J. Mueller, David A. Huse. Quasi-One-Dimensional Polarized Fermi Superfluids,
, (12 2007): 0. doi:

09/23/2013 62.00 Hui Hu, Lei Jiang, Han Pu, Yan Chen, Xia-Ji Liu. Universal Impurity-Induced Bound State in Topological Superfluids,
, (01 2013): 0. doi:

09/23/2013 63.00 Yong Xu (??), Zhu Chen (??), Hongwei Xiong (???), W. Vincent Liu (???), Biao Wu (??). Stability of p-orbital Bose-Einstein condensates in optical checkerboard and square lattices,
, (01 2013): 0. doi:

09/23/2013 64.00 Xiaopeng Li, W. Vincent Liu. Orbital coupled dipolar fermions in an asymmetric optical ladder,
, (06 2013): 0. doi:

09/23/2013 65.00 Yariv Yanay, Erich J. Mueller, Veit Elser. Magnetic polarons in two-component hard-core bosons,
, (04 2013): 0. doi:

09/23/2013 66.00 Ran Wei, Erich J. Mueller. Magnetic-field dependence of Raman coupling in alkali-metal atoms,
, (04 2013): 0. doi:

09/23/2013 67.00 Ran Wei, Erich J. Mueller. Majorana fermions in one-dimensional spin-orbit-coupled Fermi gases,
, (12 2012): 0. doi:

09/23/2013 68.00 Stefan S. Natu, Erich J. Mueller. Dynamics of correlations in a dilute Bose gas following an interaction quench,
, (05 2013): 0. doi:

09/23/2013 69.00 Stefan S. Natu, Erich J. Mueller. Dynamics of correlations in shallow optical lattices,
, (06 2013): 0. doi:

09/23/2013 70.00 Xiaoling Cu, Tin-Lun Ho. Phase Separation in Mixtures of Repulsive Fermi Gases Driven by Mass Difference,
, (04 2013): 0. doi:

09/23/2013 71.00 Xiaoling Cui, Biao Lian, Tin-Lun Ho, Benjamin L. Lev, Hui Zhai. Synthetic gauge field with highly magnetic lanthanide atoms,
, (07 2013): 0. doi:

09/27/2013 80.00 Xiaopeng Li, Erhai Zhao, W. Vincent Liu. Topological states in a ladder-like optical lattice containing ultracold atoms in higher orbital bands,
, (02 2013): 0. doi:

TOTAL: 31

Number of Papers published in non peer-reviewed journals:

(c) Presentations

"Fermion Pairing with Ultracold Atoms", R.G. Hulet, Indiana University

"Exploration of the BEC-BCS Crossover with Ultracold Lithium Atoms", R.G. Hulet, CASTU Workshop on Ultracold Atoms, Tsinghua University

"Exploration of the BEC-BCS Crossover with Ultracold Lithium Atoms", R.G. Hulet Quo Vadis BEC?, Bad Honnef, Germany

"Exploration of the BEC-BCS Crossover with Ultracold Lithium Atoms", Yale University

"Fermion Pairing with Ultracold Atoms", R.G. Hulet, Canadian Institute for Advanced Research Meeting, Vancouver

"Transport of a Bose-Einstein Condensate Through a Random Potential", R.G. Hulet, Physics of Quantum Electronics, Snowbird, UT

"Spin-imbalance of ultracold Fermions in quasi-1D", A.S. Rittner, APS March Meeting

"The Role of Interactions in Disorder Induced Damping of Dipole Oscillations of a Bose-Einstein Condensate", S. Pollack, APS March Meeting

"Fermion Pairing with Unbalanced Spins: From 3D to 1D", R.G. Hulet, KITP Workshop

"Damping of Superfluid Transport by Disorder", R.G. Hulet, KITP Workshop

"Fermion Pairing with Ultracold Atoms", R.G. Hulet, Univ. of Michigan

"Damping of Superfluid Transport by Disorder and Anderson Localization", R.G. Hulet, APS DAMOP Meeting, Univ. of Virginia

"Widely Tunable Interactions in a 7Li BEC: from Dipolar Interactions to Beyond Mean-Field", R.G. Hulet, Aspen Workshop

"Introduction to Cold Atoms and Bose-Einstein Condensation", R.G. Hulet, Varenna Summer School Lecture

"Anderson Localization and Damping of Superfluid Transport by Disorder and Defects", R.G. Hulet, Varenna Summer School Lecture

"Propagation of Matter Wave Solitons", R.G. Hulet, Varenna Summer School Lecture

"Fermion Pairing with Unbalanced Spins: From 3D to 1D", R.G. Hulet, Cargese Workshop

"The Many-body Physics of One-dimensional Systems of Fermionic Atoms in Optical Lattices at Finite Temperatures", C.J. Bolech, International Conference on Recent Progress in Many-Body Theories. Ohio State University, Columbus (July 27th - 31st, 2009).

"Dimensional Confinement and Yang-Baxter Integrability in Cold-atom Systems via Optical Lattices", C.J. Bolech, Quantum Theory and Symmetries 6. University of Kentucky, Lexington (July 20th - 25th, 2009).

"Luttinger Liquids in Trapped Ultracold Atomic Fermi Gases", C.J. Bolech, poster at APS DAMOP Meeting 2009.

"Spin-imbalanced Atomic Fermi Gases in One Dimension and the Prospects for FFLO Superconductivity", C.J. Bolech, Focus Session on BEC-BCS Crossover, APS March Meeting 2009.

"The Attractive 1d Fermi Gas: Paired States and Dimensional Crossover", C.J. Bolech, DARPA OLE Review Meeting, Las Vegas, Nevada (December 15th - 18th, 2008).

“Non-zero momentum Bose-Einstein condensation of orbital atoms", W. V. Liu, APS March Meeting, Pittsburgh, PA, Invited talk March 20, 2009.

“Crystalline superfluidity of cold atoms in lattice p-bands", W. V. Liu, Physics of Quantum Electronics Meeting, Snowbird, Utah, Invited talk, Jan 8, 2009.

“Orbital physics of optical lattices", W. V. Liu, Aspen Center for Physics Workshop, Aug 19, 2008.

“Effective theory for weakly coupled one-dimensional imbalanced Fermi gas”, E. Zhao, APS March meeting, Pittsburgh, PA, March 19, 2009.

"Reaching Strongly correlated regimes of quantum gases in optical lattices", Jason Ho, Copenhagen workshop, August 8, 2008

"A Grand Challenge in Cold Atom Physics: Reaching the strongly correlated regime of Quantum Gases in Optical Lattices", Jason Ho, Conference on Strongly Interacting Many-body systems, Paris, Sept 2008

"How to reach the strongly correlated regime of quantum gases in optical lattices", Jason Ho, CASTU Conference on Frontier of Degenerate Quantum Gases, Oct 20, 2008

"Strongly Interacting Fermi Gases", Jason Ho, CIFAR Conference on Quantum Material, Vancouver, Canada, Nov 19, 2008

"Opportunities and Grand Challenges in Cold Atom Physics: 2nd TUS International Workshop on Frontiers in Physics", Jason Ho, Tokyo, Dec 11, 2008.

"Strongly Interacting Fermi Gases", Jason Ho, Toyko University of Science, Tokyo, Dec 12, 2008.

"Mapping out thermodynamic quantities using optical lattice emulator", Jason Ho, DARPA OLE Meeting, Dec 17, 2008.

"New Challenges and Opportunities in Cold Atom Physics", Jason Ho, Colloquium, UC San Diego. Jan 29, 2009.

"Precision Measurements on Quantum Many-Body Systems", Jason Ho, UC Berkeley, Feb 7, 2009

"Current State of Quantum Simulation with Cold Atoms", Jason Ho, Kavli Institute for Theoretical Physics, February 12, 2009

"Cooling of fermions in Optical Lattices and Strongly Interacting Fermi Gases around narrow resonances", Jason Ho, Treiste Conference on Research Frontiers in Ultra-cold Atoms, 4 May 2009.

"The Wonderful World of Atoms", Jason Ho, Public Lecture, Sponsored by Chinese University of Hong Kong, Hong Kong Convention and Exhibition Center, Hong Kong, May 12, 2009

"Reducing Entropy in Quantum Gases in optical lattices", Jason Ho, Aspen workshop on quantum gases and quantum information, Aspen Center for Physics, June 5, 2009.

"FFLO state in population imbalanced Fermi gases", Han Pu, seminar at the Los Alamos National Lab, January, 2009

"Ultracold Fermi gases: from BEC-BCS crossover to FFLO", Han Pu,
seminar at Univ. of British Columbia, Oct. 2008

"Finding FFLO in population imbalanced Fermi gas", Han Pu, seminar at Institute of Physics, Chinese Academy of Sciences, Aug. 2008

1. W. Vincent Liu, 22 July 2010, NORDITA Workshop "Quantum solids, liquids, and gases," Stockholm, Sweden, 19 July —27 Aug, 2010. Invited talk: "p-orbital ultracold particles and Bose-Einstein crystal."

2. W. Vincent Liu, 25 Feb 2010, Department of Physics, Univ of Maryland, College Park. CNAM Condensed Matter Colloquium: “Exotic superfluidity of spin imbalanced fermions: from three to one dimension”.

3. W. Vincent Liu, 8 Sep 2009, Conference: Bose-Einstein Condensation 2009, Frontiers in Quantum Gases, Sant Feliu de Guixols (Costa Brava), Spain, 05-11 September 2009. Invited short talk: “Analytic thermodynamics and thermometry of 1D imbalanced Fermi gases at strong interaction.”.

4. Erhai Zhao (postdoc), “Theory of quasi-one dimensional imbalanced Fermi gases", International Symposium on Quantum Fluids and Solids (QFS 2009), Northwestern University, Aug. 2009.

5. Kaden R. A. Hazzard, "RF spectra of lattice bosons: a probe of correlations, fluctuations, and quantum criticality", DAMOP May 2010.

6. Stefan Baur, "One dimensional polarized paired
Fermi gases on a Feshbach resonance", DAMOP, May 2010.

7. David Ceperley, "The calculation of Hubbard model parameters in a disordered lattice", Quantum Fluids and Solids Satellite meeting in Grenoble (August 7, 2010).

8. David Ceperley, "Quantum Monte Carlo for Charged Systems", KITP meeting in Beijing (October 2009).

9. Leslie O. Baksmaty, "Unitary Superfluidity of Polarized Fermionic Gases in Highly Elongated Traps", DAMOP, May 2010.

10. Satyan Bhongale, "Dissipative Transport of a Bose-Einstein Condensate in an Optical Speckle Disorder Potential", DAMOP, May 2010.

11. D. McKay, "Thermalization in 1D, 2D, and 3D Spin-Dependent Lattices", DAMOP, May 2010.

12. A. S. Ritter, "Phase diagram of a one-dimensional spin-imibalanced Fermi gas", DAMOP, May 2010.

13. Randall Hulet, “Widely Tunable Interactions in a 7Li BEC: from Dipolar Interactions to Beyond Mean-Field”, BEC 2009, Sant Feliu, Sept. 6, 2009.

14. Randall Hulet, “Universal Scaling in the Recombination Rates of 7Li”, Efimov Workshop, Academia Lincea, Rome, Oct. 21, 2009.

15. Randall Hulet, “Widely Tunable Interactions in a Bose Gas: From Anderson Localization to Beyond Mean Field”, Seminar, University of Florence, Italy, Oct. 22, 2009.

16. Randall Hulet, “Widely Tunable Interactions in a Bose Gas: From Anderson Localization to Beyond Mean Field”, Colloquium, ETH, Zurich, Nov. 12, 2009.

17. Randall Hulet, “Spin-Imbalanced 1D Fermi Gas”, CECAM Workshop, ETH, Zurich, Nov. 13, 2009.

18. Randall Hulet, “Optical Lattice Simulations of Correlated Fermions”, DARPA Workshop, Miami, Dec. 3, 2009.

19. Ann Sophie Rittner, “Phase Boundaries of Imbalanced Fermions in 1D”, DARPA OLE Workshop, Miami, Dec. 3, 2010.

20. Scott Pollack, “Interaction Effects in Anderson Localization of an Ultracold Atomic Gas”, Physics of Quantum Electronics, Snowbird, UT, Jan. 7, 2010.

21. Randall Hulet, “Spin-Imbalanced 1D Fermi Gas”, NewSpin Workshop, University of Utrecht, Jan. 8, 2010.

22. Randall Hulet, “Widely Tunable Interactions in a Bose Gas: From Anderson Localization to Beyond Mean Field”, Colloquium, Texas A&M University, Feb. 4, 2010.

23. Ann Sophie Rittner, “Phase Diagram of Imbalanced Fermions in 1D”, DPG Meeting, Regensburg, Germany, March 11, 2010.

24. Randall Hulet, “Spin-Imbalance in a One-Dimensional Fermi Gas”, APS March Meeting, Portland, OR, March 18, 2010.

25. Randall Hulet, “Superfluid Dissipation and a Beam Splitter for Matter-Wave Solitons”, Nonlinear Quantum Gas Meeting, Ourense, Spain, April 14, 2010.

26. Randall Hulet, “Pairing in Unusual Places – Stretching the Realm of Superconductivity”, Colloquium, University of Heidelberg, April 16, 2010.

27. Randall Hulet, “Few Body Physics with Ultracold Atoms – The Efimov Family Tree”, Seminar, Institute for Nuclear Theory, University of Washington, Seattle, April 26, 2010.

28. Ann Sophie Rittner, “Phase Diagram of Imbalanced Fermions in 1D and the crossover to 3D”, Canadian Institute for Advanced Research Meeting, Montreal, May 7, 2010.

29. Randall Hulet, “Optical Lattice Simulations of Correlated Fermions”, DARPA Workshop, Houston, May 24, 2010.

30. Randall Hulet, “Superfluid Dissipation and a Beam Splitter for Matter-Wave Solitons”, Center for Nonlinear Studies Workshop, Santa Fe, NM, June 23, 2010.

31. Randall Hulet, “Spin-Polarization of a One-Dimensional Fermi Gas”, Strongly Correlated Electron Systems, Santa Fe, NM, June 29, 2010.

ShengQuan Zong at March 2011 APS meeting
"Validity of the scattering length approximation in strongly interacting Fermi systems"

Carlos Bolech at Kavli Institute for Theoretical Physics program on "Beyond Standard Optical Lattices"
"Polarized Two-component Fermi Gases in Elongated Traps and 2d Optical Lattices"

S. Bhongale at March 2011 APS meeting
"Dissipative Transport of Trapped Bose-Einstein Condensates through Disorder"

Jason Ho at the ICTP conference at Treiste on Strongly interacting Fermi gas
"the Upper branch Fermi gas"

Jason Ho at the Aspen Center for Physics
"the Upper branch Fermi gas"

Jason Ho at the ICTP workshop on Novel superfluid
"Ferromagnetism in Strongly Intreacting Fermi gases"

Jason Ho at INT workshop on Strongly Correlated Fermions
"strong interactions associated with narrow resonances"

Han Pu at 26th International Conference on Low-Temperature Physics
"Spin-orbit coupled Fermi gases"

Han Pu at the 7th OCPA conference
"Spin-orbit coupled quantum gases"

Han Pu at INT workshop on Strongly Correlated Fermions
"Bogoliubov-de Gennes Study of Trapped Fermi Gases"

Randall Hulet at Atomic Physics Gordon Conference
"Pairing in Polarized Fermi Gases”

Randall Hulet at DARPA OLE Workshop
“Optical Lattice Simulations of Correlated Fermions”

Randall Hulet at Aspen Workshop on Cold Quantum Gases near Resonances
“Pairing in Polarized Fermi Gases”

Randall Hulet at International Conference on Laser Spectroscopy

"Pairing in Polarized Fermi Gases"

Randall Hulet at INT workshop on Strongly Correlated Fermions
"Spin-Polarized Fermions in 1D"

Randall Hulet at April Meeting of the APS
"Universality in Three and Four-Body Efimov States"

Randall Hulet at Summer School at the University of São Paulo
"Pairing in Unusual Places – Stretching the Realm of Superconductivity"

Randall Hulet at Summer School at the University of São Paulo
"Dissipation of Superfluid Transport by Disorder and Solitons Interacting with Barriers"

W. Vincent Liu at ICTP Advanced Workshop on "Non-standard superfluids and insulators"
"p-band superfluid and insulator phases in opti- cal lattices"

W. Vincent Liu at International Conference "Frontiers of Condensed Matter Physics"
"Ultracold spin-imbalanced Fermi gases in low dimensions"

Zixu Zhang at APS March meeting
"(2kF , 2kF) density-wave orders of interacting p-orbital fermions in square optical lattice"

Xiaopeng Li at APS March meeting
"U (1) × Z2 transition from the Mott insulator to px + ipy Bose-Einstein superfluid phase"

Xiaopeng Li at KITP "Beyond standard optical lattice"
"The Bose-Einstein supersolid phase with momentum dependent inter- action"

W. Vincent Liu at DARPA Optical Lattice Emulator workshop
"U(1) × U(1) to Z2 Kosterlitz-Thouless transition of the Larkin- Ovchinnikov phase in an anisotropic two-dimensional system"

R. Hulet at Gordon Conference on Correlated Electron Systems, Mt. Holyoke College, South Hadley, MA (6/26/12), Fermions in Optical Lattices

Pedro Duarte at DARPA Optical Lattice Emulator Workshop, Chicago (5/31/12), Experimental Investigations of the 3D Fermi-Hubbard Model

R. Hulet at International Conference on Frontiers of Cold Atoms, Chinese University of Hong Kong (5/17/12), Fermions in Optical Lattices

R. Hulet at APS March Meeting, Boston (2/28/12), Spin-Imbalance in One and Three-Dimensional Fermi Gases

R. Hulet at Physics of Quantum Electronics Conference, Snowbird, UT (1/5/12) (Plenary), Three and Four-Body Efimov States in an Ultracold Atomic Gas

R. Hulet at NewSpin2 Conference, Texas A&M University, College Station (12/15/11), Pairing in Unusual Places – Stretching the Realm of Superconductivity

R. Hulet at NewSpin2 Conference Winter School, Texas A&M University, College Station (12/12/11), Ultracold Atomic Fermions in Many-Body Systems

R. Hulet at DARPA OLE Workshop, Ft. Lauderdale, FL (12/7/11), Optical Lattice Simulations of Correlated Fermions

R. Hulet at Workshop on Coherence and Decoherence at Ultracold Temperatures, Technical University Munich (9/8/11), Three and Four-Body Efimov States in an Ultracold Atomic Gas

R. Hulet at Princeton Condensed Matter Summer School, Princeton (8/11/11), Pairing in Polarized Fermi Gases

R. Hulet at Princeton Condensed Matter Summer School, Princeton (8/11/11), Dissipation of Superfluid Transport by Disorder and Solitons Interacting with Barriers

R. Hulet at Princeton Condensed Matter Summer School, Princeton (8/10/11), Tunable Interactions in Bose-Einstein Condensates - The Efimov Effect

R. Hulet at International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC), Belfast, Northern Ireland (8/2/11), Three and Four-Body Efimov States in an Ultracold Atomic Gas

T.-L. Ho at ENS Cold Atom Mini-Workshop, Fractional Charges in Cold Atoms

T.-L. Ho at Tsinghua Workshop in Synthetic Gauge Field, Some Fundamental Issues of Cold Atoms in Synthetic Gauge Fields

T.-L. Ho at DARPA OLE workshop, Fractional Charges of Cold Atoms in Optical Lattices

T.-L. Ho at APS March Meeting'12, The Upper Branch Quantum Gases

T.-L. Ho at Montpellier Workshop in honor of Prof. Lev Pitaevskii, Strongly Repulsive Quantum Gases

T.-L. Ho at International Conference on Frontiers of Cold Atoms and Related Topics, Atom Glue: Increasing the Energy Scales in Quantum Simulation

T.-L. Ho at International Conference in honor of the 90th Birthday of Prof. C.N. Yang, Challenges and Opportunities in Cold Atom Research in the Coming Decades

N. Trivedi at the Winter school on spin physics and topological defects in cold atoms, condensed matter, and beyond, Ferromagnetism

L. Jiang at DAMOP'12, Rashba Spin-Orbit Coupled Atomic Fermi Gas

H. Lu at DAMOP'12, Expansion of 1D Polarized Superfluids

H. Pu at ISCAP-V, Spin-Orbit Coupled Quantum Gases

H. Pu at DARPA OLE workshop (Dec. 2011), Axial Expansion of 1D Fermi Gases

H. Pu at Tsinghua Workshop in Synthetic Gauge Field, Rashba Spin-Orbit Coupled Quantum Gases

C. J. Bolech at LPHYS'12, Dimensional Crossover and Geometric Quenches in 1D Polarized Attractive Fermi Gases

C. J. Bolech at INES'11, Dynamics and quasi-stability in two-component imbalanced atomic mixtures or Examples of Non-equilibrium Physics in Ultracold Atomic Gases

C. J. Bolech at ICMP'11, Coupling One-Dimensional Imbalanced Attractive Atomic Fermi Gases

S. Langer at DAMOP'12, Asymptotic limit of momentum distribution functions in the sudden expansion a spin-imbalanced Fermi gas in one dimension

K. Sun at APS March Meeting'12, Tunneling-driven transitions in magnetization compressibility and density redistributions in a fermionic superfluid of cold atoms trapped in an array of one-dimensional tubes

B. Wang at APS March Meeting'12, Quantum Dynamics of Population-Imbalanced Fermi Mixture in One-dimensional Optical Lattices

X. Li at APS March Meeting'12, Time reversal symmetry breaking of p-orbital bosons in a one-dimensional optical lattice

X. Li at DAMOP'12, Topological Phase Transition in an SP-Orbital Chain

E. J. Mueller at International Conference on Frontiers of Cold Atoms and Related Topics, Spin-Orbit Coupled Interactions

E. J. Mueller at DARPA OLE workshop'12, 1D Fermions

S. Natu at APS March Meeting'12, Timescales for Equilibrationand Adiabaticity in Optical Lattices

E. Kapit at APS March Meeting'12, Non-Abelian Braiding of Lattice Bosons

D. Ceperley at Computational Physics Conference'12, Validity of the Scattering Length Approximation (SLA) in Strongly Interacting Fermi Systems

C. Yang at APS March Meeting'12, PIMC Study of Spin-Polarized 1D Trapped Fermions with Strong Attractive Contact Interaction

C. Yang at DARPA OLE workshop'12, Spin-polarized 1D Trapped Fermions: A Path Integral Monte Carlo Study

D. Chen at DAMOP'12, Reservoir-Assisted Band Decay of Ultracold Atoms in a Spin-Dependent Optical Lattice

S. Kondov at DAMOP'12, Disordered Hubbard Model with Ultracold Atoms

S. Kondov at PQE'12, 3D Anderson Localization of Ultracold Matter

B. DeMarco at ICAP'12, Reservoir-Assisted Band Decay of Ultracold Atoms in a Spin-Dependent Optical Lattice

Bath-induced band-decay in a spin-dependent optical lattice, B. DeMarco, D. Chen. C. Meldgin, DAMOP 2013

Disordered Hubbard model with ultracold atoms, W. R. McGehee, S. Kondov, B. DeMarco, DAMOP 2013

3D Anderson Localization in Variable Scale Disorder, W. Xu. W. R. McGehee, S. S. Kondov, J. J. Zirbel, and B. DeMarco, Boulder School for Condensed Matter and Materials Physics, 2013

Interplay of disorder and interactions in an Optical Lattice Hubbard Model, W. R. McGehee, S. S. Kondov, and B. DeMarco, Gordon Conference on Atomic Physics, 2013

Bath-induced Band Decay and Quasimomentum Cooling in an Optical Lattice, C. Meldgin, D. Chen, and B. DeMarco, Gordon Conference on Atomic Physics, 2013

Ultracold Fermions in a Disordered Optical Lattice, S. Kondov, Physics of Quantum Electronics conference 2013

Controlled Dynamics in Disordered Quantum Gases, B. DeMarco, KITP conference on New Directions in the Quantum Control Landscape, 2013

Localized Impurities in Ultracold Fermi Gas, Han Pu, Hangzhou Workshop on Quantum Matter, 2013

Ground State and Expansion Dynamics of a One-Dimensional Fermi Gas, Han Pu, Wolfgang Pauli Institute Workshop on Confined Quantum Systems: Modeling, Analysis and Computation, 2013

Rashba Spin-Orbit Coupled Bose Gases: Perspectives from MF and ED Studies, Ramachandhran Balasubramanian, DARPA Workshop on Optical Lattice Emulator, 2012

Universal Impurity-Induced Bound State in Topological Superfluids, L. Jiang, H. Hu, X.-Ji. Liu, H. Pu, and Y. Chen, DAMOP, 2013

Anderson Localization of Cold Atomic Gas with Effective Spin-Orbit Interaction in a Quasiperiodic Optical Lattice, L. Zhou, W. Zhang, and H. Pu, APS March Meeting 2013

FF Pairing Instability in Spin-Orbit Coupled Fermi Gas, L. dong, L. Jiang, H. Hu and H. Pu, APS March Meeting 2013

Topological and Strongly Correlated Ground States in Rashba Spin-Orbit Coupled Bose Gases, R. Balasubramanian, H. Hu and H. Pu, APS March Meeting 2013

Randall G. Hulet, "Hubbard Model with Ultracold Atoms: Observation of Antiferromagnetic Correlations", Frontiers of Quantum and Mesoscopic Thermodynamics Meeting, Prague, Czech Republic (7/31/13).

Randall G. Hulet, "Optical Lattice Simulations of Correlated Fermions", DARPA OLE Workshop, San Francisco (5/30/13).

Randall G. Hulet, "Quantum Simulations with Atoms in Optical Lattices", Workshop on New Magnetic Field Frontiers in Atomic/Molecular and Solid State Physics, Les Houches, France (5/6/13).

Randall G. Hulet, "Quantum Simulations with Atoms in Optical Lattices", Workshop on Quantum Matter, Hangzhou, China (4/23/13).

Randall G. Hulet, "Quantum Simulations with Atoms in Optical Lattices", Symposium on Cold Atom Physics, Shanghai Center for Complex Physics, Shanghai, China (4/19/13).

Randall G. Hulet, "Few Body Physics with Ultracold Atoms – The Efimov Family Tree", International Conference on Few-Body Physics in Cold Atoms, Beijing (4/11/13).

Randall G. Hulet, "Atoms in Optical Lattices – the Hydrogen Atom of Many-Body Physics", Symposium Honoring Daniel Kleppner, Sao Carlos, Brazil (2/28/13).

Randall G. Hulet, "Quantum Simulations with Atoms in Optical Lattices", Symposium on Novel Topological Quantum Matter", University of Texas, Dallas, TX (2/25/13).

Randall G. Hulet, "Quantum Simulations with Atoms in Optical Lattices", Physics of Quantum Electronics Conference, Snowbird, UT (1/7/13).

Randall G. Hulet, "Fermions in Optical Lattices", Latin American Optics and Photonics Conference (OSA), San Sebastiao, Brazil (11/12/12).

Randall G. Hulet, "Optical Lattice Simulations of Correlated Fermions", DARPA OLE Workshop, Arlington, VA (11/8/12).

Randall G. Hulet, "Fermions in Optical Lattices", Quo Vadis BEC? Meeting, Bad Honnef, Germany, (8/22/12).

W. Vincent Liu, Topological phases of fermions in the p-orbital band of optical lattices, 7th Cross-Strait and International Conference on Quantum Manipulation, 2013

W. Vincent Liu, Orbital phase transitions in low dimensional beyond-standard optical lattices, International Workshop on "Quantum Many-Body Systems in Low Dimensions", 2013

W. Vincent Liu, Topological phases of fermions in the p-orbital band of optical lattices, NorditaWorkshop "Pushing the Boundaries with Cold Atoms", 2013

Xiaopeng Li, Orbital physics in one dimensional optical lattice, APS March Meeting, 2013

Ran Wei, Erich Mueller, Majorana fermions in one-dimensional spin-orbit coupled Fermi gases, APS March Meeting, 2013

Eliot Kapit, Erich Mueller, A Vector Potential for Flux Qbits, APS March Meeting, 2013

Yariv Yanay, Erich Mueller, Superfluid Density of Weakly Interacting Bosons on a Lattice, DAMOP, 2013

Erich Mueller, Majorana fermions in one-dimensional cold Fermi gases, International Workshop on "Quantum Many-Body Systems in Low Dimensions", 2013

D. Weiss, Onset of thermalization in nearly integrable Bose gases, DAMOP, 2013

D. Weiss, Finite Temperature Non-Equilibrium Superfluid Systems, Queenstown, New Zealand, 2013

T.-L. Ho, ``Spin-Spiral States in 1D Fermi Gas at Infinite Repulsion", Hong Kong Forum, organized by University of Hong Kong, Dec 8, 2012

T.-L. Ho, ``Realizing the Pfaffian Quantum Hall State with Cold Atom Magic", IAS Asia Pacific Workshop on Condensed Matter Physics, Dec 14-16, HKUST, Hong Kong

T.-L. Ho, "Novel States and Synthetic Gauge Fields of High Spin Particles", ITAMP Workshop on Finite Temperature and Low Energy Effects in Cold Atomic and Molecular Few and Many-body Systems. March 25-27, 2013

T.-L. Ho, ``Some Key Questions and Major Challenges in Cold Atom Research", Symposium in Spin-Orbit Effects in Cold Atoms, Xioa-Tung University, organized by Anthony Leggett, Shanghai April 20, 2013

T.-L. Ho, ``The World of High Spin Particles", 2013 Hongzhou Workshop on Quantum Matter, April 22-25, 2013

T.-L. Ho, ``Spin-orbit coupling in 1D Fermi gas with infinite repulsion", Workshop on Finite Temperature and Low Energy Effects in Cold Atomic and Molecular Few and Many-body Systems. " International Workshop on Quantum Many-Body Systems in Low Dimensions, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, June 19-21, 2013

T.-L. Ho, ``How weak spin-orbit interaction can cause dramatic many-body effects in low dimension systems", Workshop on ``Synthetic Gauge Fields for Atoms and Photons", BEC Center, Trento, Italy, July 1-13, 2013

T.-L. Ho, ``Bosonic Quantum Hall States", An invited talk at Professor Lev Pitaevskii's 80th Birthday Celebration, City Hall, Trento, Italy, 6 July 2013

C. J. Bolech, "Some results in the non-equilibrium expansion dynamics of integrable systems"
The 7th annual Great Lakes Strings Conference.
University of Kentucky, Lexington (May 17th - 19th, 2013)

C. J. Bolech, "Non-equilibrium Dynamics in Low-dimensional Cold Atomic Gases".
Physics at the Falls II: Recent Progress in Nonequilibrium Quantum Many-body Theory.
State University of New York at Buffalo (May 16th - 18th, 2013)

Number of Presentations: 187.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

2009 - David Ceperley was elected a Center for Advanced Studies Professor, at the University of Illinois

David Huse: elected Fellow of American Academy of Arts and Sciences

Randall Hulet: chosen as a 2010 Outstanding Referee of the Physical Review and Physical Review Letters Journals

Randall Hulet: Willis E. Lamb Award for Laser Science and Quantum Optics, 2011

B. DeMarco, Vestal High School Hall of Fame inductee, 2012

T.-L. Ho, Fellow of American Association for Advancement of Science, 2012

T.-L. Ho, Fellow of Simons Foundation, 2012

Brian DeMarco: University of Illinois Willett Scholar Award, 2013

Han Pu. APS Outstanding Referee, 2013

Erich Mueller: Robert A. and Donna B. Paul Academic Advising Award

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Yean-an Liao	0.44	
James Hitchcock	1.00	
Tobias Paprotta	0.00	
Pedro Duarte	0.00	
Charles Mathy	1.00	
Arijeet Pal	0.57	
ShengQuan Zhou	0.95	
Hsiang-Hsuan Hung	0.17	
Qi Zhou	0.83	
Wieran Li	0.60	
Hong Lu	0.63	
Ram Balasubramanian	0.35	
Lei Jiang	0.67	
Shuaiping Ge	0.67	
Dan Goldbaum	0.50	
Stefan Baur	0.63	
Xiaopeng Li	0.40	
Zixu Zhang	0.50	
Kaden R.A. Hazzard	0.25	
Stefan S. Natu	0.63	
Eliot Kapit	0.13	
Ushnish Ray	0.81	
David Chen	0.50	
Matthew Pasienski	0.50	
Carolyn Meldgin	0.05	
Yi-Hsuan Lin	1.00	
Melissa Revelle	0.00	
Biao Huang	0.53	
Sangwoo Chung	0.83	
Hyungwon Kim	0.37	
Michael Kolodrubetz	0.14	
David McKay	0.38	
Philip Ross	0.38	
ChangMo Yang	1.00	
Bo Zhao	0.12	
Liangsheng Zhang	0.04	
Bhuvanesh Sundar	0.36	
Yariv Yanay	0.93	
Matthew Reichl	0.00	
Sayan Choudhury	0.07	
Yi-Shin Lin	0.50	
William Cole	1.00	
Yen Lee Loh	1.00	
S.-Y. Chang	1.00	
Sidong Lei	0.00	
David Tam	0.00	
Tsung-Lin Yang	1.00	
Xinxing Liu	0.30	
Lin Dong	0.00	
Wenchao Xu	0.45	
Stanimir Kondov	0.00	
William McGehee	0.00	
Shovan Dutta	1.00	
Ran Wei	0.00	
Junjun Xu	0.00	
Laura Zundel	0.00	
Timothy McCormick	1.00	

FTE Equivalent:	**26.18**
Total Number:	**57**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Wenhui Li	0.63
Ann Sophie Rittner	0.50
Theodore Corcovilos	0.88
Meera Parish	0.01
Paata Kakashvili	0.70
Leslie Baksmaty	0.84
Fei Lin	0.25
Frank Kruger	0.50
Erhai Zhao	0.73
Chungwei Lin	0.34
Ed Taylor	0.75
Russell Hart	1.00
Benjamin Olsen	0.34
Stephan Mandt	0.00
Rahul Nandkishore	0.00
Marco Schiro	0.32
Lin Xia	0.50
Jean-Felix Riou	0.10
Kuei Sun	1.00
Yean-an Liao	0.41
Bin Wang	0.50
Bryan Clark	0.00
Shizhong Zhang	0.53
Xiaolin Cui	1.00
Ann Sophie Rittner	0.35
Matthew White	0.08
Matthew Pasienski	0.08
Yen Lee Loh	0.50
Karim Bouadim	0.00
Michele Casula	0.20
Roberto Diener	0.50
Guthrie Partridge	0.00
FTE Equivalent:	**13.54**
Total Number:	**32**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
David Ceperley	0.08	
Carlos Bolech	0.08	
Randall Hulet	0.08	
Tin-Lun Ho	0.08	
Nandini Trivedi	0.08	
Brian DeMarco	0.08	
David Huse	0.08	
Vincent Liu	0.08	
Erich Mueller	0.08	
Han Pu	0.08	
David Weiss	0.08	
FTE Equivalent:	**0.88**	
Total Number:	**11**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Adrien Signoles	0.00	
Florian Emaury	0.00	
Arun Nanduri	0.00	Physics
Merritt Kerridge	0.00	Physics
Michael DeMarco	0.00	Physics
Michael Zakrajsek	0.00	
Paul Koehring	1.00	
Jean Baptiste Kerveillant	0.00	
Kevin Jourde	0.00	
Adam Reed	0.00	
Brian Henderson	0.00	
FTE Equivalent:	**1.00**	
Total Number:	**11**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
James Hitchcock	
Lei Jiang	
Hong Lu	
Pedro Duarte	
Melissa Revelle	
Lin Dong	
Total Number:	**6**

Names of personnel receiving PHDs

NAME	
Qi Zhou	
Yean-an Liao	
Kaden R. A. Hazzard	
Charles Mathy	
Zixu Zhang	
Lei Jiang	
Eliot Kapit	
Stefan Baur	
Arjeet Pal	
Michael Kolodrubetz	
ShengQuan Zhou	
David McKay	
Xiaopeng Li	
Weiran Li	
Hong Lu	
Total Number:	**15**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attachment

Technology Transfer

Final Report for period August 1, 2007 – July 31, 2013
DARPA Optical Lattice Emulator Program

Optical Lattice Simulations of Correlated Fermions
ARO W911NF-07-1-0464

Han Pu, Randall Hulet, Rice University
David Ceperley, Brian DeMarco, University of Illinois
Jason Ho, Nandini Trivedi, Ohio State University
David Huse, Princeton University
W. Vincent Liu, University of Pittsburgh
Erich Mueller, Cornell University
Carlos Bolech, University of Cincinnati
David Weiss, Penn State University

Prepared October 4, 2013 by Han Pu and Randall Hulet

Abstract

Optical lattices are employed to simulate important condensed matter materials, with ultracold atoms playing the role of the electrons in a real material. We have obtained the phase diagram of a one-dimensional (1D) Fermi gas with spin-imbalance in this way. This system features a partially polarized phase which is the 1D analog of the long-sought FFLO state. Current research is focused on direct detection of the FFLO state and explore the 1D-3D dimensional crossover. We have recently detected antiferromagnetic order in the 3D Fermi-Hubbard model using spin-dependent Bragg scattering of light. This was a major goal of our project, enabled by the development of a novel scheme to evaporatively cool atoms in an optical lattice. We have also focused on developing alternative cooling schemes, We have also investigated the connection between quantum integrability and thermalization in a 1D Bose gas, and considered equilibration and thermalization phenomena in optical lattices. Other theoretical issues, such as the effects of spin-orbit coupling, the disordered Bose-Hubbard model, and many-body localization, have also been explored.

3D Fermi-Hubbard Model at Half-Filling

The Fermi-Hubbard model at half-filling, corresponding to one particle per site, is known to exhibit antiferromagnetism. Antiferromagnetism is a property shared by most of the undoped parent compounds of high-temperature superconductors, and may be an essential attribute of these materials. The realization of antiferromagnetism in a 3D optical lattice, however, has been impeded by the extremely low temperatures that are required. The Hulet group has developed a method to perform evaporative cooling in the lattice using blue-detuned light to offset the confinement of the red-detuned optical lattice. In this scheme, blue-detuned laser beams overlap the infrared lattice beams along the three orthogonal directions, as shown in Fig. 1. Evaporation can be controlled by tuning the chemical potential of the confined atoms to near the escape threshold with the intensity of the blue-detuned beams. Significant cooling is observed. In addition, the blue-detuned light is used to keep the density fixed at half-filling during the lattice ramp-up. We apply this scheme to a 3D cubic optical lattice filled with an equal number of two hyperfine sublevels of the ^{6}Li atom.

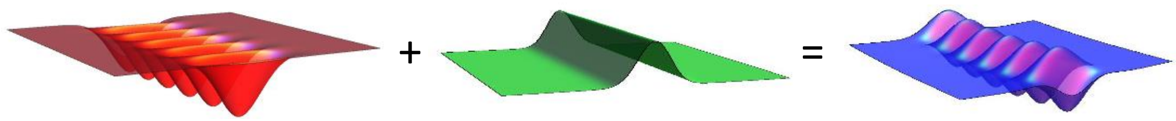

Figure 1. A green laser beam is used to compensate the overall confining potential from a conventional lattice potential.

The beams are aligned with a relative precision of 1 μm using the three identical copies of the assembly portrayed in Fig. 2. The purpose of the compensating beams is two-fold. First, by raising the chemical potential of the atoms confined to the lattice, it offers the opportunity for atoms to evaporatively cool from the outer regions of the lattice, as depicted in Fig. 3. Secondly, our team has shown theoretically (Mathy, Huse, and Hulet, Phys. Rev. A **86**, 023606, 2012) that the region of antiferromagnetism may be enlarged by proper choice of the relative intensities and beam sizes of the green beams, relative to the IR beams. Those conditions have been incorporated into the experiment.

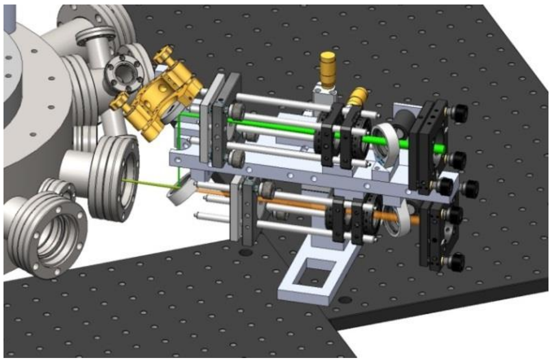

Figure 2. Schematic of the experimental setup.

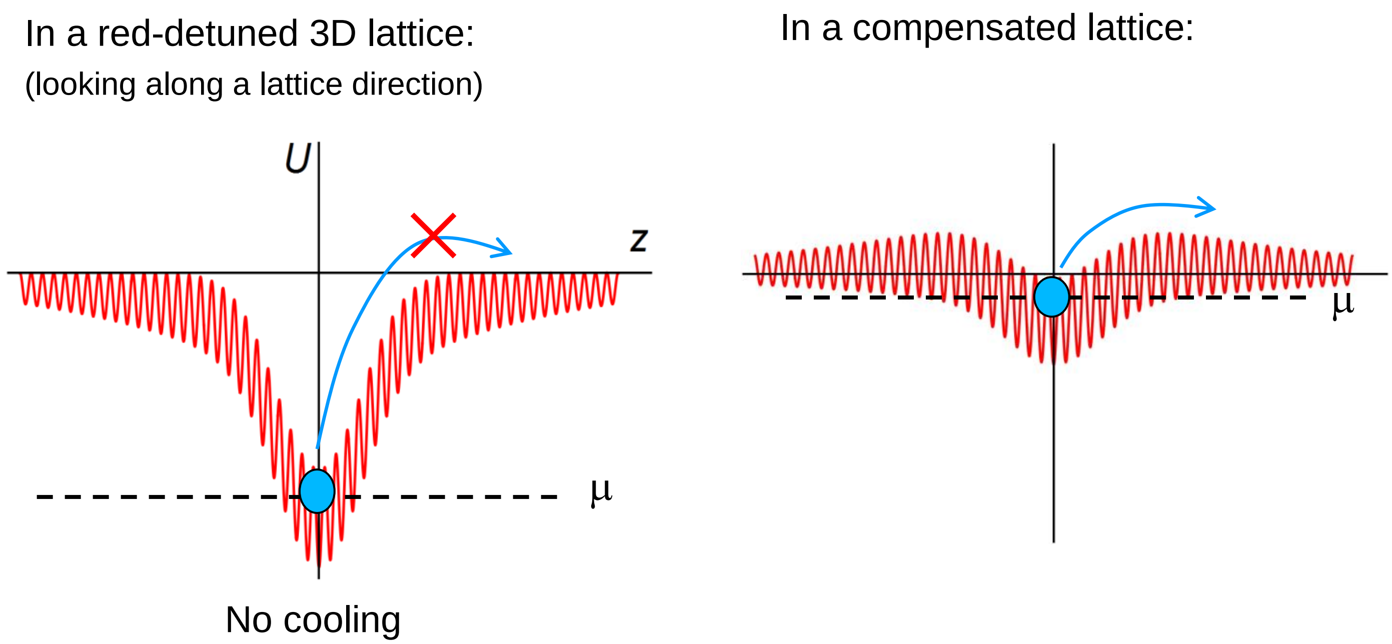

Figure 3. A blue-detuned compensating beam helps to improve the cooling efficiency inside lattice.

We have loaded over 10^5 atoms into the lattice at a magnetic field corresponding to a scattering length of approximately 300 a_o. The lattice order was detected by Bragg scattering of light tuned to near the 2s-2p resonance. By tuning the incident angle of the Bragg beam to 51° with respect to a lattice plane (001 direction) and collecting the scattered light with a lens, we were able to detect a huge Bragg scattering signal. The signal vs. lattice depth fits to the shape given by the Debye-Waller factor, as shown in Fig. 4. This experiment demonstrates that Bragg scattering produces a high-signal-to-noise, easily detectable signal, which we will exploit to detect anti-ferromagnetic order.

Bragg scattering from the symmetry planes corresponding to antiferromagnetic order is not as strong or as forgiving as the 001 Bragg scattering. In order to be spin sensitive we tune the Bragg probe in between the two spin states corresponding to the pseudo-spin ½ system. No signal is present without some magnetic ordering, and this only begins when the system is sufficiently close to the Néel transition. This transition temperature is predicted by theory to be a maximum of ~0.03 T_F. By adjusting the intensity of the compensating green beams to be as large as possible without significantly distorting the overall confinement shape, we detect a Bragg signal that is ~50% above the background of diffuse scattering. A “rocking curve” showing the angular distribution of this Bragg signal is shown in Fig. 5. The angular width corresponds to a correlation length of ~4 sites, which quantum Monte Carlo calculations show is a temperature that is perhaps twice T_N. By adjusting the parameters of the green compensating beams we hope to cool further and to sharpen the Bragg signal.

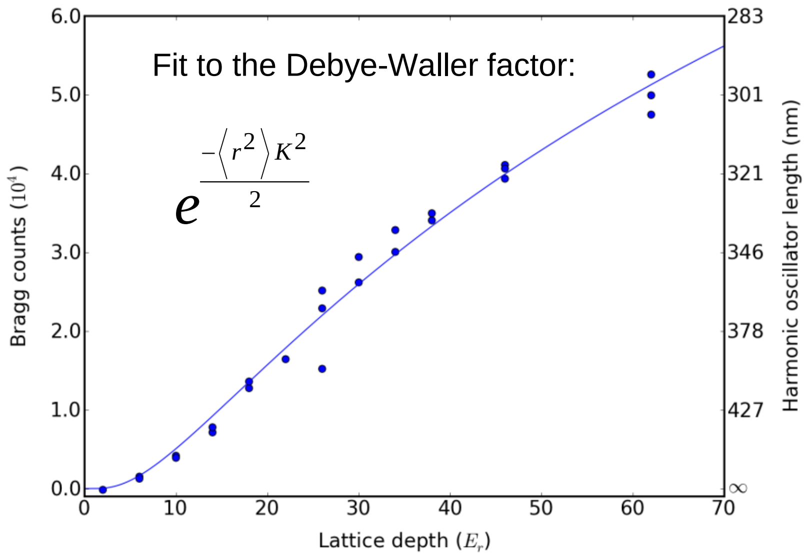

Figure 4. Bragg signal from the 3D square lattice potential.

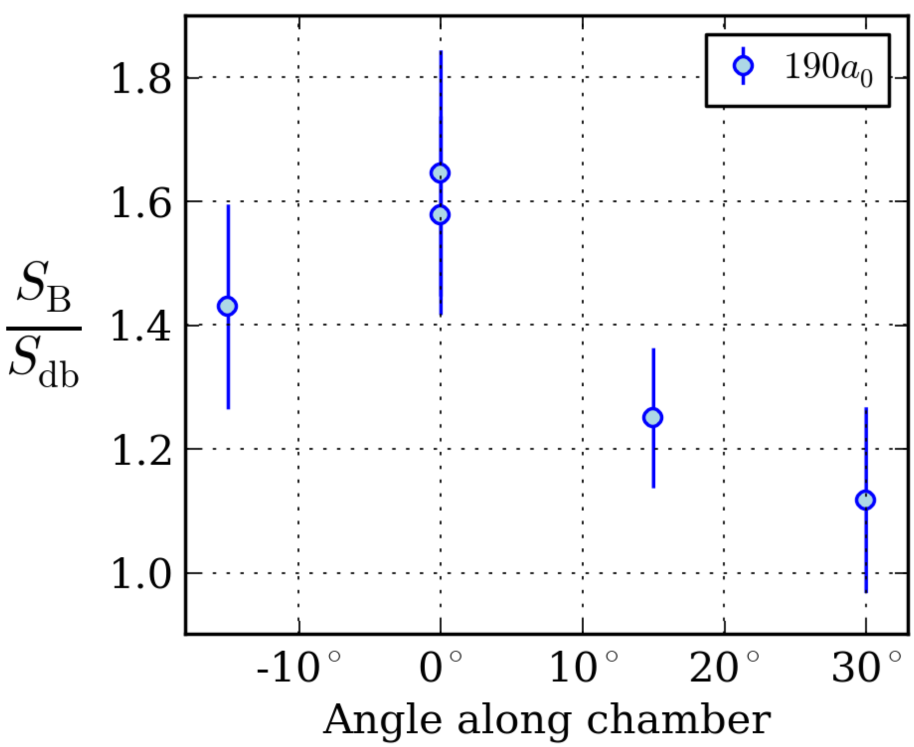

Figure 5. Rocking curve (angular distribution) of the antiferromagnetic Bragg signal.

Trivedi's group has analyzed the magnetic correlations in the 3D Hubbard Hamiltonian using determinantal quantum Monte Carlo on up to 10^3 lattices, including the effects of population imbalance. Their aim is to guide the Rice experimental search for antiferromagnetism by calculating the temperature dependence of the antiferromagnetic structure factor and thereby determining the temperature scale at which recent experiments might be operating. They show that changing the density away from half-filling, or the spin polarization away from zero, within the expected experimental uncertainties, does not significantly affect the results at the identified temperature. By comparing simulations of the Hubbard and Heisenberg models they have determined the extent of finite size effects close to the Néel transition. Figures. 6 and 7 plot the antiferromagnetic structure factor as functions of interaction strength U and temperature T, respectively.

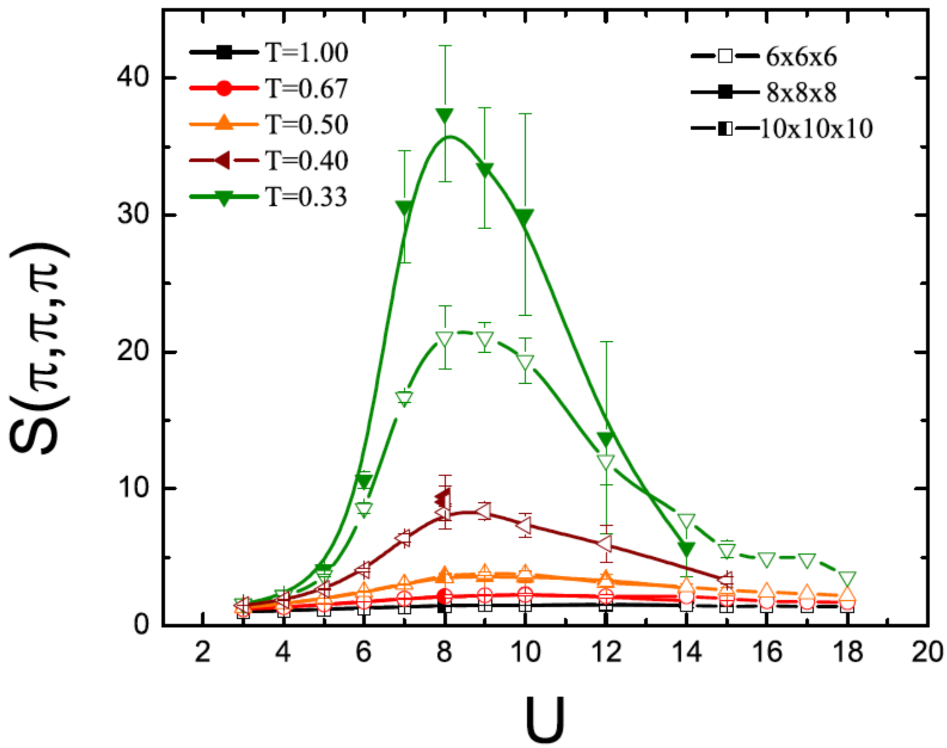

Figure 6. For a fixed temperature T, the antiferromagnetic structure factor is peaked at U~8=10t reflecting the non-monotonic behavior of T_{Neel} which peaks at this optimal U value. This suggests the optimal value that should be used in experiments.

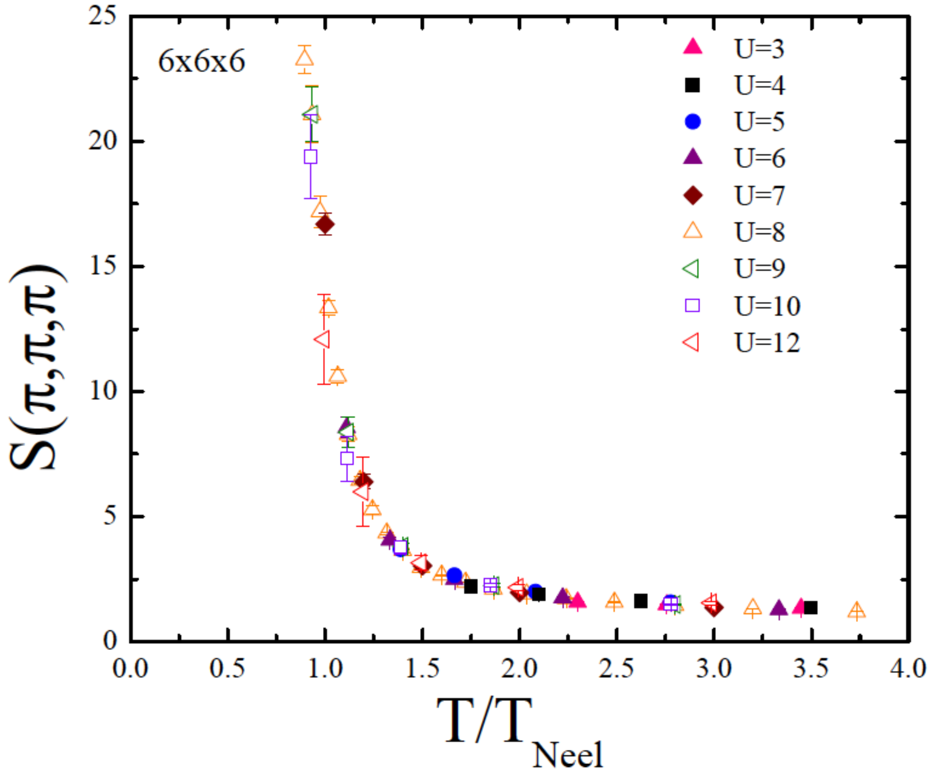

Figure 7. Scaling behavior of the AF structure factor when plotted as a function of T/T_{Neel} for various U.

Liu's group has investigated physics beyond the single-band model. They discovered that the mixing between even and odd orbitals, such as *s* and *p*, is equivalent to a partial Rashba spin-orbital coupling when the orbital space (*s*, *p*) is identified as pseudo-spin 1/2, hence *emergent effective spin-orbital coupling*. They further extended this study to the case of a two-dimensional array of such ladders (i.e., a 2D array of 1D atomic "tubes"). Upon crossing over to such a quasi-two-dimensional system, the edge modes from individual ladder form a parity-protected flat band at zero energy. Those zero modes are shown to be the equivalent of decoupled Majorana fermions.

<u>One-Dimensional Polarized Fermi Gas</u>

We continue to upgrade the apparatus used to produce polarized Fermi gases, and the laser system, in particular. Our focus is the direct detection of the FFLO superfluid state. Our approach is to detect the non-zero center-of-mass momentum pairs that are the hallmark of the FFLO mechanism. To do this, we have constructed a blue-detuned "anti-confining" laser system that flattens the axial harmonic potential, while maintaining confinement radially. This laser system is nearing completion, and we expect to measure time-of-flight momentum distributions in the next few months.

Theoretical studies of expansion dynamics of 1D Fermi gas have been carried out by Bolech's and Pu's groups using unbiased numerical techniques such as density-matrix-renormalization-group and time-evolving-block-decimation methods. Such studies show that the time-of-flight expansion in 1D is highly nontrivial and provide better understandings of the signature of the FFLO pairing.

The dimensional crossover is another important phenomenon that we are investigating using this system. The phase diagram of a trapped Fermi gas with population imbalance is sensitive to the dimensionality. Liu's group tackled this problem by investigating the 1D dynamical evolution of an initial state prepared to mimic the ground state of the 3D system. Bolech's group considered the coupling between an array of 1D tubes and performed a mean-field calculation based on the Bogoliubov-de Gennes equations to find the phase diagram of the system. It is shown that the magnetization of the system undergoes an incompressible-compressible transition as a function of magnetic field and intertube tunneling strength (see Fig. 8).

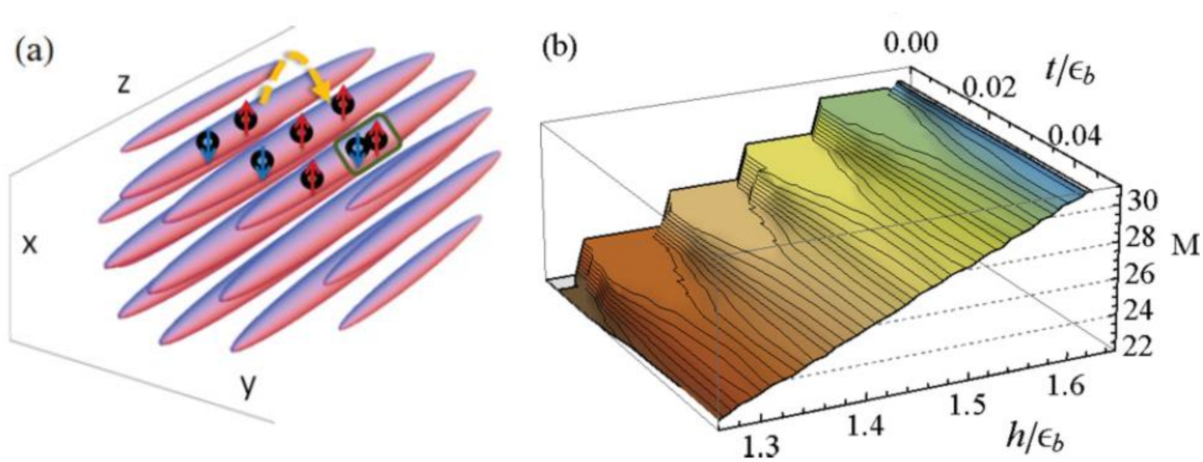

Figure 8. (a) Illustration of the coupling between a 2D array of tubes. (b) Filling imbalance per tube, *M*, in a radially uniform system as a function of chemical potential difference (or magnetic field) , *h*, and intertube tunneling, *t*. The lobe-like plateaus represent magnetic incompressible states with corresponding integer filling, while the outside region has finite compressibility. [From Sun and Bolech, Phys. Rev. A **85**, 051607(R) (2012)]

Equilibration and Thermalization

The development of new lattice cooling techniques will play a critical role in experiments that aim to probe quantum phases that are currently out of reach. DeMarco's group has developed a new Raman cooling technique that works for any atomic species trapped in an optical lattice and does not require a spin-dependent lattice or bath. The basic scheme, which is closely related to traditional evaporative cooling, is shown in Fig. 3a. The atoms are trapped in a lattice and are prepared in one hyperfine ground state *F*. Two-photon stimulated Raman transitions are used to transfer high quasi-momentum atoms to an excited band in another hyperfine state *F'*. Those atoms are then removed using near-resonant light that only affect atoms in state *F'*. The remaining atoms collide and rethermalize to lower temperature. The cooling rate for this technique can be very high, since the Raman rate is limited by the excited-state bandwidth, which is one to two orders of magnitude larger than that of the ground band.

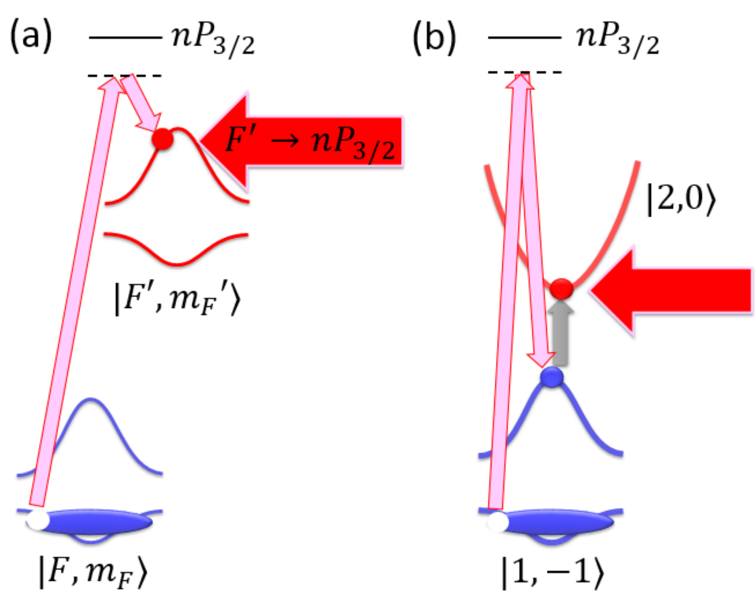

Figure 9. Raman cooling method shown in terms of the band structure. The general technique (a) involves Raman lasers (light red arrows) driving atoms between hyperfine states in a quasi-momentum selective way. Proof of principle data was acquired showing the variant in (b), in which microwaves (gray arrow) are used to transfer atoms between hyperfine states.

DeMarco's group demonstrated this technique in a proof-of-principle measurement using ^{87}Rb atoms trapped in a spin-dependent lattice. Figure 9b shows this variant of the method, which involves transferring atoms from ground to the first excited band in the $|1,-1\rangle$ state using a stimulated Raman transition. Adiabatic rapid passage driven by a microwave-frequency magnetic field is used to transfer only the atoms in the excited band to the $|2,0\rangle$ state (which does not experience the lattice), where they are removed using resonant light.

Typical images before and after a single cooling step are shown in Fig. 10. The quasi-momentum spread of the atoms is reduced and condensed fraction is increased. Data demonstrating this cooling effect are shown in Fig. 11 for different hold times in the lattice after the cooling is performed. This measurement represents the first demonstration of direct cooling quasi-momentum in an optical lattice.

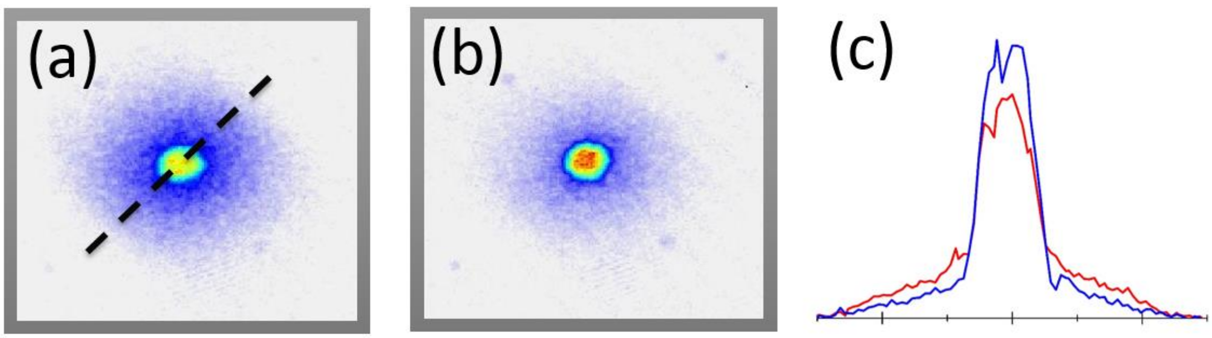

Figure 10. Images showing evidence for cooling. Data is shown for a gas before (a) and after (b) a cooling pulse is applied. In (c), traces through the image along a lattice direction (dashed line) are shown before (red) and after (blue) cooling.

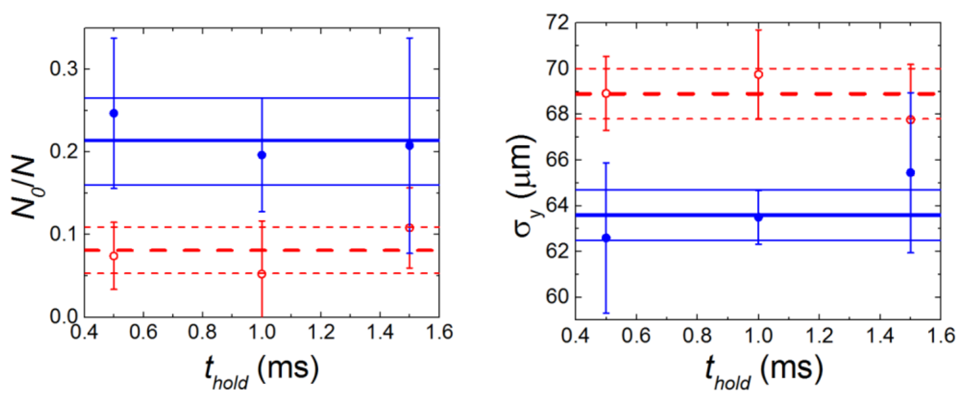

Figure 11. Data showing cooling for different hold times after the cooling pulse. Data are shown with (blue) and without (red) a cooling pulse. The lines indicate the average and standard deviation taken across hold times. Cooling increases condensate fraction N_0 / N and reduces the rms size σ_y of the gas, which is proportional to $\sqrt{T}$.

The primary limitation on this method is sensitivity to magnetic fields at the mG level. DeMarco's group is now developing a laser system to implement the most general version of this scheme (Fig. 3a) using the Raman-driven magnetic-field-insensitive transition between the $|1,0\rangle$ and $|2,0\rangle$ states. A sweep of the Raman detuning will be used to continuously cool the gas.

In a strong theory-experiment collaboration, the DeMarco group and the Mueller group studied the dynamics of the number of condensed atoms, following a lattice ramp. In a work published in Physical Review A as a rapid communication [Stefan S. Natu, David C. McKay, Brian DeMarco, and Erich J. Mueller, Phys. Rev. A **85**, 061601], they showed that the condensate fraction evolves significantly on a 100 microsecond timescale. A positive consequence of this rapid response is that local equilibrium is readily maintained during lattice ramps. A negative consequence is that "bandmapping" techniques, which rely on changing the lattice parameters quickly compared to the response time, are not able to give quantitative information about such systems. These results will be fed back into our attempts to produce better cooling protocols. Further theoretical support came from Ceperley's group who, using quantum Monte Carlo techniques, have computed entropies, condensate fractions and momentum distributions for bosons in 3D optical lattices and are completing a comparison with DeMarco's experiments. This will be used to better characterize experimental densities and temperatures.

In related theoretical studies [Stefan S. Natu, Erich J. Mueller, arXiv:1201.6674], the Mueller group used perturbation theory to study both density-density correlations and momentum distributions of a Bose gas after suddenly turning off interactions in the lattice. They found that correlations spread ballistically, with a speed given by the sharpest part of the single-particle dispersion. Quite surprisingly, they found that the ramps to zero interactions shared all of the qualitative features of experiments in the strongly interacting regime [Cheneau *et al.* Nature **481**, 484 (2012)] -- interactions only renormalized the propagation speed. They are now using Bogoliubov theory to push these calculations to stronger interactions.

In collaborating with DeMarco, Ceperley's group have used quantum MC to further studies of several different lattice systems. The first involves comparisons with experiments conducted at DeMarco group for the clean Bose-Hubbard model in a trap. This study involved N ~ 200,000 particles and focused on possible thermometry in experiments by calibrating against QMC results. The work has been completed and will be sent for publication shortly; it calls into question the equilibration of these systems at high entropy near . Their second project is on disordered systems. They have performed ab initio calculations to compare directly with experiment - the first of its kind and can explain the absence of the re-entrant superfluid phenomena. They are currently in the process of understanding the different features arising in the trap induced heterogeneity, e.g., how the different domains coexist and transform. Towards this end they have undertaken massive parallel computations of the phase diagram including disorder averaging.

David Huse's group is interested in spin and energy transport in universal Fermi gases. They investigated the superdiffusive nonequilibrium dynamics of a single impurity atom in a low temperature single-species Fermi gas [Hyungwon Kim, David A. Huse, Phys. Rev. A **85**, 043603 (2012)], and also worked out the diffusive transport behavior of the polarized Fermi gas, including heat transport, spin Seebeck and spin Peltier effects. In addition, they also studied nonequilibrium critical dynamics of the quantum Ising spin chain and of the Boson Mott insulator in a tilted potential [Michael Kolodrubetz, Bryan K. Clark, David A. Huse, Phys. Rev. Lett. **109**, 015701 (2012)] , showing universality between the cold-atom "model" studied in Greiner's lab and the Ising spin chain.

Huse's group continued their study on many-body localization. They have found a new statistical mechanics of phases and phase transitions within the many-body localized regime. These phases and phase transitions show up in the dynamics and in the exact many-body eigenstates of an isolated quantum many-body system, but are invisible to the equilibrium thermodynamics. The new ordered phases (including topologically ordered phases) are dynamically protected by the many-body localization against their equilibrium instability to thermal fluctuations. This opens up new possibilities for stable quantum memories.

In another work, they explained a sense in which a system whose eigenstates are all many-body localized can be viewed as an integrable system with localized conserved operators. These localized conserved operators do interact, and this causes dephasing, and entanglement that spreads logarithmically in time.

They also explored eigenstate phase transitions that occur within the ferromagnetic phase of an infinite-range Ising model that obeys the Eigenstate Thermalization Hypothesis: the exact eigenstates are "Schrodinger cat states" and have phase transitions in the dynamics of how they tunnel or thermally excite themselves to flip between the "up" and "down" magnetized phases. They are also exploring nonequilibrium steady states with energy currents flowing between two reservoirs.

During the past few months, Weiss' group has finally disentangled all heating and loss processes in their Quantum Newton's Cradle experiments, and they found a way to calibrate the expected rate of diffractive three-body collisions, by referencing it to the 3-body inelastic loss rate. They see evidence for the onset of thermalization due to weak non-integrability in a 1D gas, but with a time constant that is ~10 times slower than conventional theory predicts (see Fig. 12). This suggests that the conventional statistical mechanics that underpins the Boltzmann equation cannot be applied too close to integrability, and strongly hints that there may be a quantum KAM regime, a regime away from integrability where systems still do not conventionally thermalize.

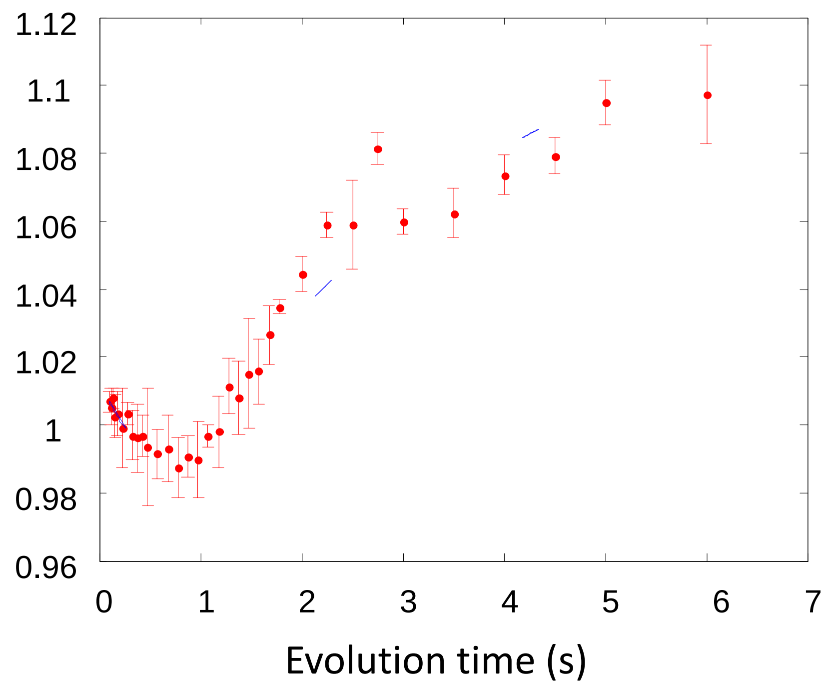

Figure 12. Evolution of the total energy in a dense quantum Newton's cradle [ref: T. Kinoshita, T. Wenger, and D.S. Weiss, "A quantum Newton's cradle", *Nature* **440**, 900 (2006)]. The dip at early times results from evaporative cooling due to diffractive 3-body collisions, while the energy increase comes mostly from spontaneous emission. The cooling rate is 10 times slower than predicted for these conditions. Because of the absence of diffractive 2-body collisions in this system, this may be also the first observation of elastic 3-body collisions.

Other Theoretical Issues

In addition to those mentioned above, our team have explored various theoretical issues that are not necessarily tied closely to the experiments carried out in the Hulet and DeMarco labs, but are broadly related to the OLE program.

Ho's group has continued the study of strongly interacting Fermi gases, with focus on obtaining thermodynamic information of strongly interacting Fermi gas through its density profile. In the previous funding periods, Ho's group has discovered algorithms to process the density to obtain thermodynamic functions and to determine phase transitions at finite temperatures and zero temperature (T=0). His group has demonstrated the algorithm for attractive 1D Fermi gas, which has only T=0 but not finite T transitions. In the last funding cycle, they have extended this study to repulsive Fermi gas, which is related to the controversy of the discovery of ferromagnetism reported by the Ketterle group. They have shown that all the purported phenomena for ferromagnetism can be accounted for by Pauli blocking physics in the so-called upper branch of the energy spectrum. In this funding cycle, they have extended this study to Fermi gases with narrow resonances and to repulsive Bose gases. In addition, they have shown recently that ferromagnetism in a spin-1/2 Fermi gas is the (equal mass) limiting case of phase separation in a binary mixture of Fermi gases, and have proven a theorem that phase separation (the analog of ferromagnetism) must occur for sufficiently large mass asymmetry. In addition, Ho's group continues to explore new ways to increase the energy scale of lattice gas systems by exploring the interaction between a lattice gas with another atomic species not confined by the lattice which acts as an agent that induces effective long-range interaction.

Ceperley's group has done exact numerical calculations of few fermion systems where scattering length is on the order of the inter-particle spacing, which is important since many of the OLE experiments are done in this regime. They have seen how underlying molecular states influence scattering states and determined that the ferromagnetic transition density is changed by a factor of two if one includes the underlying molecular states, in agreement with the experiment of Jo *et al*. They have developed techniques to generalize this technique from the lattice model into the continuum.

Liu's group has investigated topological phases of fermions in optical lattices. This research is broadly related to the Fermi-Hubbard model project, which is part of the core thrusts of the OLE program. Cold fermionic atoms were discovered to exhibit topological semimetal and insulator phases, both being related to the current on-going hot topics in Condensed Matter physics.

Both Mueller's and Pu's groups have explored the effects of non-Abelian synthetic Gauge field on cold atoms. Mueller's group has conducted a number of numerical experiments to evaluate the feasibility of observing non-Abelian statistics with cold atoms. In a paper published in Physical Review Letters [Eliot Kapit, Paul Ginsparg, and Erich Mueller, Phys. Rev. Lett. **108**, 066802 (2012)] they numerically implemented a long-discussed thought experiment. In the experiment one imagines having a system in the fractional quantum Hall regime (an exotic state found in semiconductor heterostructures in large magnetic fields). One uses two lasers to produce two potential wells. One then imagines slowly moving the laser spots, switching the location of the wells. According to variational calculations, one should be able to perform quantum computation by a sequence of such moves. Kapit *et al*. numerically conducted this experiment, verifying that it works. They also proposed a cold-atom experiment which would demonstrate this physics. Pu's group has studied the effects of spin-orbit coupling in quantum gases induced by the non-Abelian Gauge field. They have shown that a properly engineered spin-orbit coupling term can greatly enhance fermionic pairing and may lead to exotic topological phases in both Boson and Fermi gases.

Both Bolech and Trivedi studied Bose-Hubbard model. Bolech studied a Bose-Hubbard model having on-site repulsion, nearest neighbor tunneling, and ferromagnetic-like coupling between the nearest-neighbors' occupation parities. For a uniform system in any dimension at zero tunneling, they obtained an exact phase diagram characterized by Mott insulator (MI) and pair liquid phases and regions of phase separation of two MIs. For a general trapped system in one and two dimensions, they performed quantum Monte Carlo and Gutzwiller mean-field calculations. Both of which show the evolution of the system from a superfluid to a wedding-cake structure of MIs with the occupations jumping by 2, as the parity coupling increases. They also identified an exotic pair superfluid at a relatively large tunneling strength. Their model ought to effectively describe recent findings in imbalanced Fermi gases in two dimensional optical lattices.

Motivated by the experimental realization of synthetic spin-orbit coupling for ultracold atoms, Trivedi's group have investigated the phase diagram of the Bose-Hubbard model in a non-Abelian gauge field in two dimensions (α is the spin-orbit coupling strength and λ is the relative strength of bosons of opposite spin). Using a strong coupling expansion in the combined presence of spin-orbit coupling and tunable interactions, they find a variety of interesting magnetic Hamiltonians in the Mott insulator (MI), which support magnetic textures such as spin spirals and vortex and Skyrmion crystals. An inhomogeneous mean-field treatment shows that the superfluid (SF) phases inherit these exotic magnetic orders from the MI and display, in addition, unusual modulated current patterns. They present a slave-boson theory which gives insight into such intertwined spin-charge orders in the SF, and discuss signatures of these orders in Bragg scattering, *in situ* microscopy, and dynamic quench experiments.

Several groups have investigated the properties of quantum gases subject to synthetic spin-orbit coupling. Together with his collaborators (Ben Lev, Xiaoling Cui, and Hui Zhai), Ho has shown that the heating due to the added laser fields which generate the spin-orbit coupling is substantially reduced if one uses Lanthanide atoms rather than the alkalis. Both Mueller's and Pu's group have studied the "Majorana modes" in spin-orbit coupled topological Fermi superfluids. Ho's group also completed a work on the spin-orbit effects in 1D repulsive Fermi gas. It was shown that at infinite repulsion, where the system has infinite spin degeneracy, even a weak spin-orbit interaction can lead to the generation of exotic phases such as a large spin spiral.